Report on Joint Stanford-Berkeley Carbon Capture and Sequestration Workshop

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and Jocelyn Rodgers (LBNL)

Funded by Lawrence Berkeley National Laboratory

Joint BioEnergy Institute, Emeryville, CA

Monday July 6^{th}, 2009

Executive Summary

This meeting was convened in order to look for possible areas of collaboration between Stanford and Berkeley in carbon capture and sequestration (CCS) research. The participants exchanged information between various research areas and tried to understand the challenges inherent in a variety of strategies for CCS. This discussion across a multitude of fields related to CCS led to the formulation of possible focus areas for a collaborative endeavor.

In the following document, we seek to describe in more detail the considerations in the various areas discussed during the workshop and highlight coherent and constructive research goals from a very broad view.

The main conclusions of the workshop were:

- At present it is unclear what the targets for the amount of CO_2 in the atmosphere will be. Most scenarios include targets for reductions of CO_2 emissions from fossil fuels in the short term, but many climate models indicate that negative CO_2 emissions will be necessary in the long term. It is important that the CCS research portfolio can accommodate these uncertainties; options for CCS technologies should be created for many different scenarios.

- Carbon capture and sequestration is unique in its scale. Implementation of research options at this large scale may have many surprising consequences. Obtaining a thorough understanding of the implications of scale for the research efforts should become an integral part of the research portfolio. As these consequences are not limited to technological aspects, the research portfolio should include an understanding of the economical and sociological impacts of these novel CCS technologies.

Recommendations arising from the workshop included:

- CCS research will benefit from an integrated research effort in which various options for novel CCS technologies are developed. Detailed research plans should be developed for the three routes of possible CCS technologies: (i) physical, (ii) chemical, and (iii) biological sequestration.

- In parallel, a research program should be initiated that allows us to evaluate the impact of novel and existing CCS technologies. These impact studies will provide important feedback to the research program.

The combination of Stanford, UCB, and LBNL has the unique expertise to develop an internationally leading research program in this field. The strength of the program will be the research aspects. For the development aspects, partnering with other institutes such as NETL is envisioned.

Outline

1 Introduction

This workshop for carbon capture and sequestration was called in order to look for areas where a colloboration between CCS researchers at LBNL, UCB, and Stanford would yield fruitful and important contributions to carbon capture and storage. The participants heard about on-going research across a broad swath of specialties and began to formulate as a group what they see as the outstanding issues in carbon capture and storage.

In order to apply some structure to the discussion, carbon capture and sequestration (CCS) was divided into three categories:

- physical,
- chemical, and
- biological.

Physical CCS includes the currently most-advanced technologies for carbon capture and sequestration; however, the development of other techniques for CCS through biological or chemical means would also be beneficial and help expand the portfolio of options for CCS in the future. Any new means for CCS which do not store carbon in geological formations should likely lead to new energy sources; energy is one of the few resources consumed on the scale that carbon is being released into the atmosphere.

None of these scientific approaches to carbon capture and storage can be considered fully distinct from the broader landscape in which CCS will occur. As such, the workshop also considered a variety of points related to industrial constraints, economic realities, global impact on CO_2 emissions, and societal acceptance. One of the guiding principles of this discussion is that no aspect of CCS, whether physical, chemical, or biological CCS, can be considered in a vacuum distinct from the other approaches and from the world in which such technologies will be deployed. Possibilities for CO_2-capture sources include air, the transportation sector, and power plants. Much of the workshop discussion was focused on capture from stationary, moderately concentrated sources of CO_2 such as flue streams from power plants, but the other CO_2 sources may be important to examine, depending on the CO_2 emissions-targets needed.

The workshop agenda is included as Appendix B, and nearly all presentations from the workshop are available at http://www.lbl.gov/dir/eih/ccs/presentations.html. Therefore, in the body of this document we do not attempt to do justice to the full range of research ideas and other input presented at the workshop. Rather, we attempt to highlight the important broader concerns and outstanding questions identified in each area. While some ideas below are attributable to specific presenters, as is evident from the presentations at the workshop website, many are the result of discussion amongst many participants.

2 Physical Capture and Sequestration

The category of physical capture and sequestration envelopes most technologies for carbon capture and storage which are on their way toward industrial implementation, as shown in Figure 1. Physical capture essentially means techniques to separate CO_2 from gas mixtures such as flue gases. Physical storage predominantly implies all modes of geological sequestration.

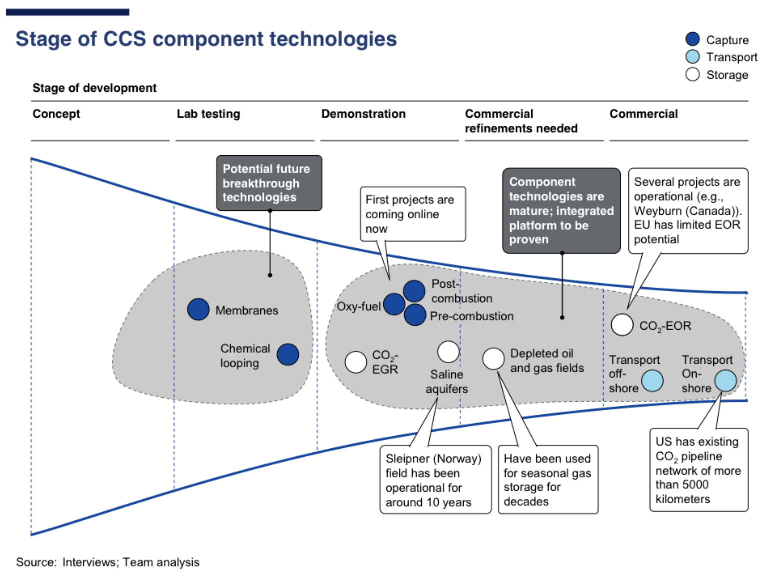

Figure 1: *Schematic from the introductory talk by Berend Smit, indicating a variety of CCS technologies and their progress towards commercialization. Picture taken from the McKinsey & Company Climate Change Special Initiative report "Carbon Capture and Storage: Assessing the Economics," 2008.*

Given the current greenhouse gas crisis and the immediate need for reducing our carbon footprint while new, potentially carbon-neutral energy sources are being developed, these approaches to CCS are absolutely crucial. In particular, geological sequestration is the only currently viable approach for carbon storage which has the necessary capacity. The need for making such approaches to CCS more robust and broadly applicable on a short time scale is huge.

LBNL and UCB have recently had two Energy Frontiers Research Centers (EFRCs) funded by the Department of Energy to study physical carbon capture and physical carbon storage. One of the important considerations for developing a Berkeley-Stanford collaboration is the best way to interface with the basic scientific research conducted at the EFRCs. The EFRC related to the capture of carbon dioxide predominantly focuses on synthesis, characterization, and prediction of nanoscale properties of novel gas separation materials. The carbon storage EFRC focuses on the properties and interactions of complex fluids and minerals at elevated temperature and pressure, in order to allow the control of flow, dissolution, and precipitation in subsurface rock formations.

These EFRCs may be viewed as focusing on the basic science of capture and geological sequestration, predominantly at the nanoscale. However, for both capture and storage, there is need to progress beyond the nanonscale to the industrial scale for capture and to the reservoir and basin scale for sequestration. An integrated facility would offer the opportunity to bring together researchers that understand different aspects of physical capture and storage and yield new inherently multiscale approaches to a variety of opportunities in the field.

Physical Capture Several of the identified opportunities for physical capture are

- Rapid synthesis of possible new capture materials and subsequent characterization of these synthesized materials. Lessons learned from the carbon capture EFRC could lead to new high-throughput evaluation of broad classes of materials.
- Identification of good adsorption systems amongst the variety of good adsorbers identified on the molecular level. This would serve as a link between the basic scientific research in the carbon capture EFRC and the ability of the materials to work at the industrial scale needed for carbon capture. This could require the development of new multiscale modeling techniques.
- Development of alternative cycling strategies for regenerating carbon capture materials and extracting the captured CO_2 for subsequent storage. Current temperature and pressure cycling can be quite expensive; are there alternate paths?

Physical Sequestration For geological sequestration, opportunities for study include

- Understanding multi-scale effects in geological sequestration, building from the nanopore level focused on in the storage EFRC to the kilometer-scale fields actually used for sequestration.
- Understanding the impact of variability of materials such as gas shales on the large-scale geological storage capacity. How can shales be used to expand the capacity of CO_2 storage while minimizing risks?
- Consideration of geological sequestration approaches in conjunction with other systems that cross typical research boundaries. Examples include compressed-air energy storage, geothermal energy systems, and the growth of algae in brine pools formed from pressure release in saline aquifers used for storage. Furthermore, the landscape of even established approaches like enhanced oil recovery might change if CO_2 use resulted in tradeable carbon credits.
- Understanding of how to optimize the overall carbon sequestration process, including how to improve suboptimal storage sites, with, *e.g.*, the development of self-sealing cap rocks.

Interface between Capture and Sequestration Finally, an opportunity that will apply for every subsequent section is determining how to best and most efficiently integrate the capture and storage processes. As shown in Figure 2, there are a wide variety of capture sources and options, and for each, the optimal approach to capture *and* sequestration are likely different. Understanding how capture and storage integrate together could very well lead to further optimization of overall processes.

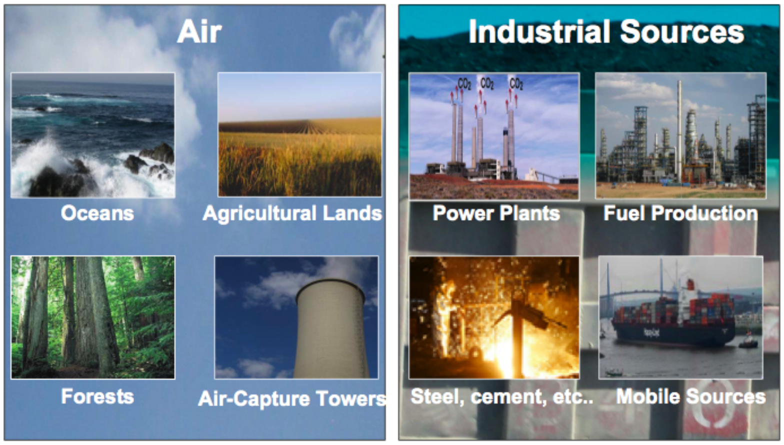

Figure 2: *Schematic presented by Sally Benson indicating the wide range of options for carbon capture.*

3 The Broader Context of Carbon Capture and Sequestration

In order for carbon capture and sequestration to have a net impact on the anthropic carbon footprint, development of CCS technologies should include consideration of

- industrial realities at the sites of CO_2 generation,
- economic validity of various capture and storage options,
- social acceptability of these options, and
- the net environmental impact of considered CCS approaches.

Often these considerations are not all weighed simultaneously, nor do they directly inform the basic scientific research being pursued. Such integration was viewed as a broad opportunity and need. Furthermore, addressing many of the questions raised in the broad categories above introduces active research questions in other (non-scientific) fields. The talks in this section of the workshop attempted to introduce a variety of these questions and considerations.

In essence, the discussion in this portion of the workshop emphasized practical considerations arising from the global scope of carbon capture and sequestration and need for wide-scale implementation. These considerations also infused the discussion in other sections of the workshop as well.

Material and Economic Considerations As shown, in Figure 3, the amount of CO_2 currently released into the atmosphere dwarfs any current usage of carbon. The scope of the CO_2-release problem will lead to a whole new level of material usage. For any chemical to be feasible for use in CO_2 separation or storage, this material must be regenerated in order to not deplete the world supply of the material. Furthermore, any product resulting from CO_2 sequestration must be consumable on the scale of energy in order to not flood the world market. Limitations on land-use and water-supply must also be considered in any process. Furthermore, all such uses should be considered on a competitive basis across various approaches to CCS.

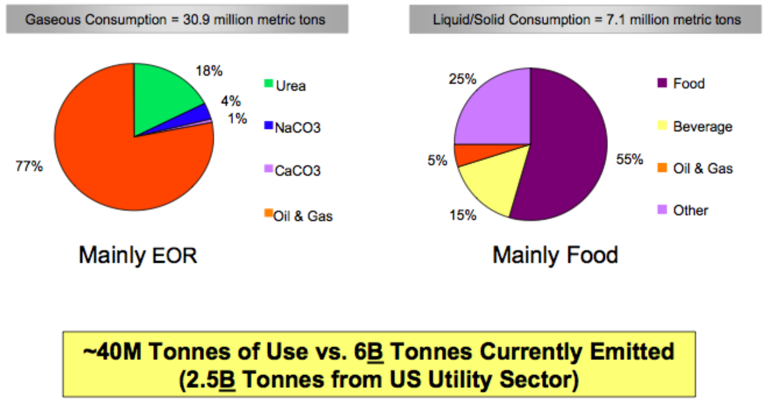

Figure 3: *Diagram of carbon consumption from the talk by Abhoyjit Bhown based on data from Howard Herzog at the MIT Laboratory for Energy and the Environment.*

Thermodynamic Considerations For physical separations of gases, the entropy of mixing places a lower bound on the energetic cost of such a process; for separating CO_2 from flue gases, the minimum energy cost from output power is 3.5%. The entropic cost of separation from dilute CO_2 in air will be substantially larger. Furthermore, converting CO_2 to fuels essentially requires reversing a combustion reaction; even if this energy comes from a renewable source, such energetic cost must be weighed against other possible uses of the energy.

Science Across the Scales In the energy fields, there is often a disconnect between the basic chemistry and material science, the process engineering, and the realities at the scale of an entire plant. Breakthroughs could be accelerated via collaboration across all these scales. One example of such considerations might be that, even after separation, CO_2 from flue gases will never be pure, and so any catalytic or biomimetic processes applied to flue gases should be robust in the presence of other gaseous components.

Understanding the Global Impact This can be viewed from both a monitoring and a modeling perspective. The ability to track successful carbon sequestration is important for understanding the climate impact as well as for stability in a carbon-credit economy. Approaches for CCS on a grand scale must be understood for both their economic cost and their climate impact. Ideally, modeling of the application of various CCS approaches on this grand scale could help identify the relevant bottlenecks that further basic science research could improve. However, improved modeling approaches are needed to accurately reflect the inherent uncertainties in such models.

Allowing for heterogeneity of approaches for local realities Many aspects of CCS are local such as the details of implementation at existing factories and in different geological formation and the societal acceptance of such approaches in various areas. This heterogeneity suggests that a portfolio of possible CCS approaches will be important and that furthermore this heterogeneity can inform the study of various approaches.

4 Chemical Capture and Sequestration

While physical capture and sequestration is by far the most developed approach to CCS, chemical CCS and biological CCS offer the opportunity to expand the portfolio of options available for CCS. In the short-term, geological sequestration is unquestionably the most viable for the large amount of CO_2 that must be stored in order to have a measurable impact on CO_2 emissions. However, novel approaches likely using some chemical or biological transformation have the possibility of improving aspects of geological sequestration or offering completely new routes for CO_2 sources ranging from the power sector to the transportation sector to air. At present, these chemical and biological approaches may not be as viable economically, but exploration of novel directions at the level of basic research is important in order to not rule out very different but effective approaches.

The discussion of chemical capture and sequestration involved both novel routes for CO_2 to form a fuel stock and ways to improve current industrial scale approaches with lessons from chemistry. Points discussed included:

Essential role of catalysis Catalysts with high turnover rate can transform the efficiency of a CO_2 chemical conversion process by orders of magnitude. Currently biological catalysts have by far the most efficient turnover rate, but progress is being made developing inorganic catalysts with high turnover rates for CO_2 conversion. In developing these catalysts, stability against other components of flue gases and earth-abundance of chemical constituents should be considered.

Chemical routes to Absorption Cycling Currently carbon capture materials are regenerated for further use by stripping the CO_2 through temperature or pressure cycling. However perhaps there are chemical (rather than physical) forms of pumping and regeneration. Also, perhaps direct chemical conversion of the bicarbonate ion resulting from absorption of CO_2 into alkaline solutions is possible rather than attempting to strip the CO_2 itself from such a solution.

New Paths to Fuel Stock Novel reaction routes could perhaps reduce CO_2 straight to a liquid fuel precursor via solar energy. For such routes, collaboration with the Helios SERC could be very fruitful. A storable fuel could possibly be relevant for the transporation industry, one of the large contributors to CO_2 emissions. However, for these paths, careful comparison of energetic costs and land-use costs must also be included in the development of research targets for these processes to be competitive.

Coupling of Combustion and Sequestration A system for coupling the coal-combustion process with the process for sequestration in a saline aquifer which could be overall more efficient was presented. This raised the question of whether other optimized processes are possible through analysis of all steps of electricity generation and CO_2 storage.

5 Biologically-Inspired Carbon Capture and Sequestration

This section on biologically-inspired CCS essentially had a dual focus. One possibility for such CCS is at industrial sites, capturing carbon from flue streams either with organisms or with systems inspired by cell machinery. Another possibility is in global-scale biosequestration. Topics discussed included:

Understanding the Global Carbon Cycle A large fraction of the world's carbon supply is currently sequestered in lifeforms and soil and tundra, as shown in Figure 4. By understanding terrestrial fluxes of carbon and the modes of carbon fixation and stabilization in the soil, we may better gauge the fundamental limits of natural terrestrial capture and sequestration. As one example, the world's forests are currently a carbon sink, but this is at least partly because many forests were cut down over the last couple centuries and trees are now regrowing. As another example, a large amount of methane is sequestered in the arctic as methane hydrate; as the earth warms, this CH_4 may be released into the atmosphere resulting in a destructive positive feedback loop since CH_4 is a stronger greenhouse gas than CO_2. Knowledge of the global carbon cycle will help define research targets for carbon sequestration, but it can potentially also help identify new routes to carbon fixation.

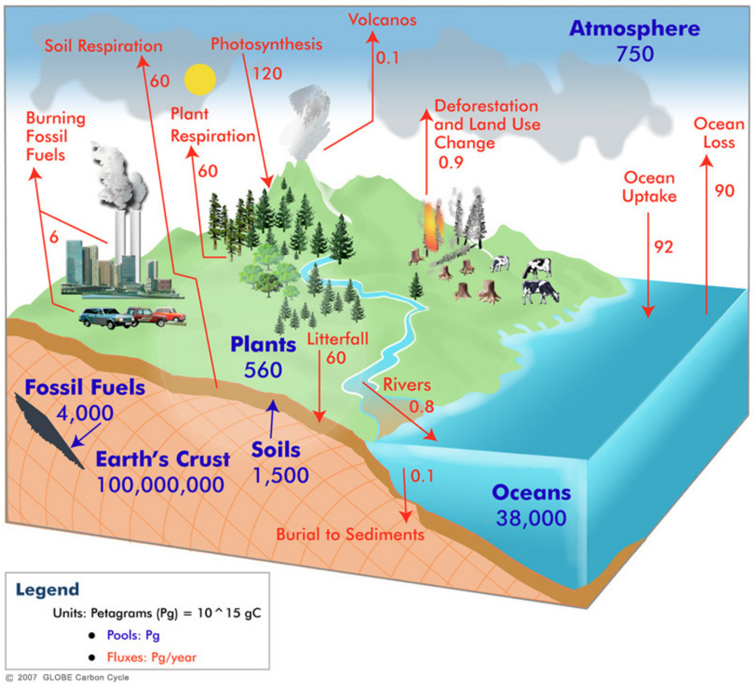

Figure 4: Diagram of the global carbon cycle presented by Jan Liphardt, indicating the current state of terrestrial carbon stores and rate of fluxes. The source of this material is the GLOBE Web site at http://www.globe.gov/. All Rights Reserved.

Need for Compatible Life-Cycle Analysis Much discussion centered around the competitiveness of biosequestration approaches relative to other approaches. One clear conclusion is that there is a need for lifecycle analysis across all CCS approaches which is mutually compatible and easily compared. This lifecycle analysis should include various considerations raised such as energy-use and land-use.

Using Organisms for In Situ Refining Subterrestrial organisms potentially offer the possiblity of novel *in situ* refining which can lead to cleaner burning fuels like hydrogen or methane resulting from hard-to-access fossil fuel stores.

Different Approaches for Different Capture Modes Since the biological CCS discussion focused on both industrial CCS approaches as well as more broadly-ranged biosequestration, it was clear that the considerations for organisms for flue-stream capture and for direct-air capture are very different. Direct-air capture will likely need to be addressed in order to deal with CH_4 release from the tundra since that is a huge continental area.

Biomimetic Carbon Capture and Mineralization Nature offers lessons on carbon capture and sequestration in minerals that we can learn from. For example, the carboxysome is a bacterial organelle for fixing CO_2 that naturally separates out the bicarbonate ion. This could potentially be coupled with nucleation of calcium carbonate to fix CO_2 in a mineral. Questions of calcium supply or alternate mineralizations need to be addressed to understand the overall capacity of such an approach. Organisms also carry out biomineralization; for example, the Cliffs of Dover were built by algal biomineralization. The time scales of that process were geological, but perhaps lessons can be gleaned from the mechanism.

Biological versus Chemical Catalysis This point came up in both the chemical and biological CCS discussions. Microbes have advantages over current chemical catalysts in that that they are solar, self-repairing, reproducing, and catalytic. In that sense, they are highly efficient catalytic systems. However, in contrast to chemical catalysts, biologically-based catalysis raises difficult issues if organisms need to be bioengineered. The culture may evolve back towards the less-efficient, unengineered organisms. Additionally, engineered microorganisms will be challenging to keep separate from natural ecosystems.

6 Broad Challenges for Moving Forward

In this section, we seek to summarize some of the broader considerations that sweep across multiple areas, as defined above. In our view, addressing the array of considerations below is best done in a highly integrated research environment which spans many basic research approaches as well as extending toward consideration of near-commercial level scale-up.

Integration across all scales A theme arising for many of the research areas is that integration across scales from nanoscale to industrial implementation or global implementation is important. Having knowledge about fundamental molecular processes, industrial scale-up, and global climate impact (to name a few areas) under one roof could potentially lead to the definition of ground breaking research targets. The need for this integration also suggests that partnerships with industry or other projects like EPRI, NETL, and WESTCARB may prove crucial since such ventures have substantial knowledge about industrial-level scale-up of processes. Such a broad effort could achieve the goal of allowing for the exploration of many new approaches while improving the identification of promising approaches, as shown in Figure 5.

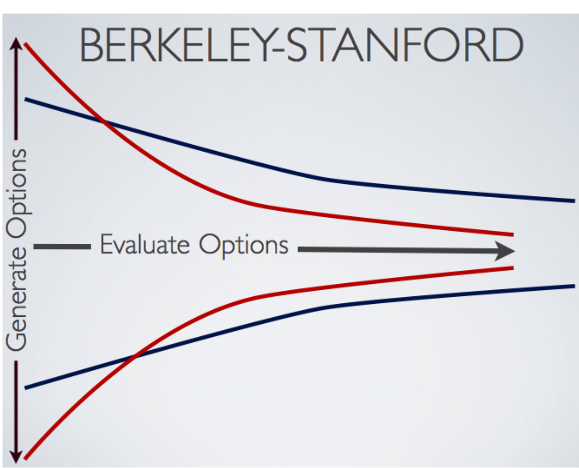

Figure 5: *Schematic presented by Berend Smit, indicating a desired outcome of a highly collaborative effort on CCS – a broadening of the basic options explored and a greater efficiency in preparing those options for commercial implementation.*

Separation and Sequestration are inextricably linked Research on carbon separation without simultaneously understanding what will be done with the separated carbon could lead to sub-optimal separation strategies. These processes will be linked at almost any implementation site and therefore should be considered together when defining research goals as well.

CCS for now and the future Traditional CCS must be optimized and better understood in order to allow for immediate large-scale implementation. However, study of novel processes for CCS could be advantageous a few decades from now. In fact, depending on the targets for carbon emissions set and whether there is a need to decrease the overall concentration of greenhouse gases in the atmosphere, the novel processes could be crucial for achieving the targets.

Optimization for different carbon sources Optimized solutions for carbon capture and sequestration may be distinct for different industrial configurations, both stationary sources like power plants and mobile sources in the transit sector. Almost certainly no single catch-all solution exists which will be optimal for all configurations of CO_2 generation and sequestration. Furthermore, solutions appropriate for direct air capture will be quite different. Therefore looking at whole processes and various local constraints will be important for developing a portfolio of solutions, each optimal for different situations.

Environmental context In general the goal of carbon capture and sequestration is to mitigate the harmful effects of the greenhouse gas CO_2 on the atmosphere. Therefore, understanding the impact of various CCS strategies on the climate is important. Furthermore, other environmental actors such as CH_4 release from the tundra should also be considered, in particular because CH_4 capture and sequestration may be targetable via similar strategies.

Coherent framework for comparing technologies The need for this framework was apparent when discussing approaches to CCS from different disciplines. A single framework for life cycle analysis of different CCS approaches could lead to much more fruitful discussions of the pros and cons of different tacts towards CCS. In particular for the more nascent approaches (chemical and biological CCS), these practical considerations can be used to identify bottlenecks and develop research targets. At the level of basic research, innovation should be *informed* but not *hindered* by practical considerations.

Acknowledgments

We thank Lawrence Berkeley National Laboratory for financially supporting this workshop and the Joint BioEnergy Institute for hosting the workshop. In addition, we thank Marian Harris, Karin Levy, and Drew Danielson for all their contributions in organizing the workshop.

A Participants

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B Workshop Program

Links to the presentation files may be found at the conference website.

Introduction

9:00 AM *Welcome* – Berend Smit (LBNL/UCB)

9:10 AM *The Challenges for CCS* – Sally Benson (Stanford)

Physical Capture and Sequestration

9:40 AM *Introduction to Energy Frontiers Research Centers at LBNL and UCB*

- Jeff Long (LBNL/UCB) – *Carbon Capture EFRC*
- Don DePaolo (LBNL/UCB) – *Carbon Storage EFRC*

10:00 AM *Brainstorming framed by Short Presentations*

Two-Slide Presentations

- Lou Durlofsky (Stanford) – *Computational Issues for Modeling and Optimizing CO_2 Sequestration*
- Steven Kaye (Wildcat Discovery Technologies) – *High Throughput Gas Separation and Storage Tools*
- Curt Oldenburg (LBNL) – *Some Beneficial Uses of CO_2 in Subsurface Systems*
- Lynn Orr (Stanford) – *Research Issues for Enhanced Oil Recovery and Coal Bed and Basalt Storage*
- Mark Zoback (Stanford) – *A Strategy for Enhanced Recovery and CO_2 Sequestration in Gas Shales*

11:00 AM Discussion

The Broader Context of Carbon Capture and Sequestration

11:30 AM *The Scale of the Problem*

- Abhoyjit Bhown (Electric Power Research Institute)

12:00 PM Brainstorming framed by Short Presentations

Two-Slide Presentations

- Ron Cohen (LBNL/UCB) – *Verification of Greenhouse Gas Emissions Reduction*
- Karl Gerdes (Chevron) – *Industrial Perspective on Cost, Energetics, and Scale*
- Isha Ray (UCB) – *Incorporating Public Perceptions of CCS in Energy Policy*

- Alan Sanstad (LBNL) – *Improving Modeling of Economy, Climate, and Energy Policy to Support CCS R&D*

Chemical Capture and Sequestration

1:30 PM *Overview of Chemical CCS, Stripping, and Utilization*

- Clifford Kubiak (UCSD)

2:00 PM Brainstorming framed by Short Presentations

Two-Slide Presentations

- Caroline Ajo-Franklin (LBNL) – *Catalysts for Capture and Mineralization*
- John Arnold (UCB) – *Clean Oxidation Process and Chemical Feedstocks*
- Chris Edwards (Stanford) – *Coupling Energy Processing and Carbon Storage*
- Jon Ellman (LBNL/UCB) – *Towards a Renewable Chemicals Industry*
- Heinz Frei (LBNL) – *Conversion to Fuel via Sunlight*
- Zahid Hussain (LBNL) – *What the Advanced Light Source Can Offer for CCS*
- Jeff Long (LBNL/UCB) – *Catalytic Reduction for* CO_2

Biologically-Inspired Carbon Capture and Sequestration

3:30 PM *Overview of Biological CCS*

- Jan Liphardt (LBNL/UCB)

4:00 PM Brainstorming framed by Short Presentations

Two-Slide Presentations

- Terry Hazen (LBNL) – *Microbial Enhanced Hydrocarbon and Hydrogen Recovery*
- Christer Jansson (LBNL) – *Algal Cultures for Biofuel, Carbon Capture, and Biosequestration*
- Janet Jansson (LBNL) – *LBNL Efforts on Biosequestration*
- Cheryl Kerfeld (LBNL/JGI) – *Biological Carbon Capture and Fixation in Bacterial Microcompartments*
- John Tainer (LBNL) – *Algal Biosequestration*

Conclusion

4:50 PM *Remarks* – Berend Smit (LBNL/UCB)